Thermography of Metallic and Composite Structures - review of applications

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ABSTRACT

The paper presents selected applications of active thermography for damage detection in metallic and composite structures. Two thermographic methods were considered, namely the pulsed thermography and vibrothermography. The performance of both methods is compared for a laminated composite specimen with barely visible impact damage. The thermal signal reconstruction method with additional processing steps is applied for processing pulsed thermography data in order to improve detection capabilities and automatically quantify the extent of damage. The results obtained with both pulsed thermography and vibrothermography are compared with the well-established ultrasonic C-Scan technique. In addition selected applications of vibrothermography in metallic structures is presented, including a case study for weld testing in steel samples and rivet testing in aircraft components.

Keywords: pulsed thermography, vibrothermography, composites, damage detection, Thermal Signal Reconstruction, nondestructive testing
INTRODUCTION

Nondestructive testing (NDT) is becoming an inseparable part of modern engineering applications. Increasing design complexity, the use of new materials and high requirements for reliability of structures require continuous development of testing methods for detection and evaluation of structural defects. A number of different testing methods have been developed for damage detection including visual inspection, passive and active approaches based on ultrasonic signals, liquid penetrant testing, radiographic and thermographic methods among others [1-3]. The family of thermographic methods is recently gaining more attention in scientific literature and in engineering applications [1]. The most important advantages of thermographic methods are: noncontact measurement, fast acquisition time, simple test setup, usually consisting of a single camera and exciter, and simple measurement procedure, which requires no extensive staff training. Thermography found many practical applications in industries such as: aerospace, renewable energy, automotive or civil engineering [4-5].

Thermography, like all nondestructive testing methods, has its limitations that may hinder the performance and even prevent successful detection in certain applications. One of the challenges in thermographic testing is quantitative evaluation of the results (damage type, shape, depth). Accurate interpretation of the results can be achieved by a qualified operator based on his experience, however the automation of the process is very difficult, which significantly increases the overall cost of the system. Different image processing techniques aim to address this problem and facilitate the interpretation of thermographic testing data. One of the basic approaches in pulsed thermography is the Thermal Signal Reconstruction technique [6-7].

This paper aims at reviewing some of the applications of pulsed thermography and vibrothermography in detecting damage in laminated composites and metallic parts. Comparison of the detection effectiveness and data processing is presented and discussed.

DESCRIPTION OF TEST METHODS

The two thermographic approaches considered in this study were pulsed thermography and vibrothermography as shown in Figure (1). Pulsed thermography is active thermographic technique with external excitation. Thermal excitation is applied to the sample’s surface by means of thermal waves generated by infrared lamps, halogen lamps or hot-air pistols. Thermal waves propagate through the sample and when they come across a discontinuity the propagation path is altered, which can be observed as changes in surface temperature distribution. The experimental setup presented in Figure (1a) consists of: thermal wave source, and infrared camera, control unit and PC class computer with data processing software. Vibrothermography is based on a completely different mechanism than optical thermography. Instead of thermal energy the acoustic waves are used to excite the system. Sonic waves propagate in the material and when they find internal defect they trigger the dissipation of vibration energy into heat mainly by friction between the contacting surfaces of the defect. Subsequently heat is conducted to the surface where it can be detected by IR camera. Experimental setup consists of: ultrasonic vibration source, infrared camera, control unit and PC computer with data processing software (Figure 1b). Ultrasonic vibration source is typically an ultrasonic welding setup that includes: piezoelectric transducer which consists of a stack of piezoelectric crystals bolted between two metal pieces, a booster (amplitude coupler) which amplifies the signal, and a sonotrode which is responsible for transferring signal to the tested specimen. This setup enables high power narrowband frequency wave generation.
Fig.1: Two basic experimental arrangements of active thermography: with external excitation (a) and with internal excitation (b).

Both techniques have their advantages and disadvantages which makes them better suited for certain applications. Pulsed thermography is sensitive to voids and inclusions in the material which are difficult to detect by vibrothermography. On the other hand, surface cracks typical for fatigue damage, which are almost undetectable for pulsed thermography, generate significant amount of heat during vibrothermographic testing. It makes vibrothermography well suited for detecting closed cracks or delaminations.

**COMPOSITE SPECIMEN**

The test sample was a rectangular laminated composite plate with \([0\theta/\theta_0\theta]_z\) ply stacking sequence. The dimensions of the plate were 120x420x2 mm as shown in Figure (3). The plate was laminated from Seal Texipreg\textsuperscript{®} HS160/REM carbon/epoxy prepreg with 61.5% fibre weight fraction and autoclaved. After manufacturing plate was introduced in the composite plate using a drop-weight impact testing tower with a hemispherical indenter (mass = 2.3 kg, diameter = 12.5 mm). A pneumatic impactor catching mechanism was used to prevent multiple impacts on the plate. During testing, the composite specimen was simply supported on a steel plate with a rectangular opening 45 mm x 67.5 mm in size. The composite plate was subjected to two impacts at adjacent locations close to the main symmetry axis of the plate. The distance between the impact points was approximately 12 mm. The energy of the first impact was equal to 3.9 J and the energy of the second impact was equal to 6 J.

Fig. 2: Analyzed composite plate (left) and details of the laminate structure (right)
Impact damage was analyzed using ultrasonic C-scan testing. The plate was scanned in pulse-echo mode by a 50 MHz transducer and the complete ultrasonic waves acquired at each scanning point were processed by selecting the appropriate gate width and position in order to obtain images of the delamination at the desired through thickness depth [8]. The composite plate was scanned from both sides and the information obtained was recombined to a single three dimensional image. The extent of damage as reconstructed by C-scan is shown in Figure (4). The identified area of delamination was approximately 326 mm$^2$.

![Image](6J impact 3.9J impact 10mm)

**Fig. 3**: Ultrasonic C-Scan of damage

**EXPERIMENTAL MEASUREMENTS**

Experiments were performed using both pulsed thermography and vibrothermography methods [9]. Temperature maps of the damaged area were obtained from measurements and are shown in Figure (4). Three dimensional temperature maps were obtained using ThermoAnalysis software package [10].

![Image](a) (b)

**Fig. 4**: TNDT results: pulsed thermography in reflection mode (a) burst vibrothermography (b).

Vibrothermographic measurements were performed with a 35 kHz ultrasonic excitation source working at 30% power (maximum power 2000 W) for 500ms. Increase of temperature on the damaged area was shown in Figure (5a). Figure (5b) shows time evolution at the two markers over delamination p1 (red curve) and over undamaged area p2 (green curve). Behavior of the two cases is completely different and there is no problem in distinguishing between damaged and healthy areas.
Figure (6) shows results of pulsed thermography measurements in the reflection mode. Markers p1-p4 are located over damaged areas, marker p5 is placed over healthy area. Figure (6b) shows temperature evolution at four points on the damaged area (black, blue, yellow and orange curves) and one on undamaged one (red curve). Barely visible square in the upper left corner is a marker tape with an area of 5x5mm with a different emissivity than the sample.

The presence of damage can be easily identified, but the evaluation of the extent of damage is not straightforward. For this reason additional thermal image processing steps were required in order to calculate the area of damage and compare it with the ultrasonic C-Scan results.

**THERMOGRAPHIC SIGNAL RECONSTRUCTION**

Thermographic Signal Reconstruction (TSR) [6,7] is a well-known method used in thermal nondestructive testing (NDT). The TSR method is based on assessment of the behavior of the logarithmic time-temperature curves. Logarithmic time history of each pixel can be fitted by function described by n-th degree polynomial (4).
\[
\ln(T) = \sum_{n=0}^{\infty} a_n (\ln t)^n = a_0 + a_1 \ln t + \cdots + a_n (\ln t)^{n-2}
\]  \hspace{1cm} (4)

Results from pulsed thermography measurements obtained in the previous step were processed by the TSR algorithm. Figure (7) shows a single frame from the raw (a) and reconstructed (b) image sequences. Raw and reconstructed images are very similar, with the reconstructed image having a slightly better contrast.

![Raw (a) and reconstructed (b) thermal image](image)

**Fig. 7:** Raw (a) and reconstructed (b) thermal image

Figure (8) shows temperature evolution for one image pixel in raw sequence (a) and reconstructed sequence (b). Reconstructed curve is perfectly smooth.

![Time evolution for raw (a) and reconstructed data (b)](image)

**Fig. 8:** Time evolution for raw (a) and reconstructed data (b)

Figure (9) shows the first derivative for raw (a) and reconstructed (b) sequences. Time evolution shows a significant amount of noise in the raw data (Fig 9c). In the case of reconstructed data, first derivative is a smooth. In derivative images signal-to-noise ratio is highly improved compared to raw signal. Higher order derivatives can be easily evaluated in the TSR method, by the existence of time history data in the algebraic form, however, the most important information is contained derivatives of 1\(^{st}\) and 2\(^{nd}\) order.
Improvement in signal-to-noise and signal-to-background ratio, obtained with TSR, facilitates the process of damage quantification. Further processing steps include the use of automated thresholding and binarization [11]. Figure (10) shows binarized image obtained from reconstructed sequence. Median filter was applied to remove high frequency noise. The marker located in the upper left corner was used to determine the surface area-per-pixel. The calculated area of damage equals $366 \text{ mm}^2$ as compared to the area of $326 \text{ mm}^2$ obtained by ultrasonic C-scan.

Fig. 10: Binarized image of damage in the analyzed composite plate.
WELD TESTING

The effectiveness of vibrothermography in detecting closed cracks was verified on a welded steel sample. The test sample was a steel plate 200×100×10 mm. The plate was manufactured to contain welding defects of known type and size, which was verified after manufacturing by ultrasonic testing. Two types of defects were confirmed: 21 mm long crack at the root of the weld located 18 mm from the longer edge of the plate (Fig 11a) and a 19 mm long lack of root fusion located 58 mm from the longer edge of the plate (Fig 11b).

The measurement was performed on a vibrothermography test system at AGH-UST. Ultrasonic converter was exciting the sample at 35 kHz and 500 W power for 1 second. The infrared camera was observing the root of the weld.

The results of Vibrothermographic test performed on the sample are shown in Figure (12). Positions of both root crack and lack of root fusion damages were identified. Defects are clearly visible.

Fig. 11: Weld specimen (c) and cross sections of: root crack (a), lack of root fusion (b)

Fig. 12: Result of vibrothermographic test on the analyzed welded sample.
RIVETS TESTING

Vibrothermographic measurements were also carried out in order to test the ability to identify loose rivets. Tests were performed on the fuselage and wing panels of Mikoyan MiG-29 [1]. Tests were performed using the mobile vibrothermographic test system [10]. The measurements were conducted directly on the aircraft, without disassembling the panels. Ultrasonic excitation was applied for 500 milliseconds using a handheld excitation device operating at 35 kHz and 500 W power. A sequence of thermal images with the total duration of 5 seconds was recorded.

Figure (13) shows the results of vibrothermographic tests. White circles in Figure (13) illustrate the location of all rivets in the analyzed region. An increase of temperature was detected in the area around one of the rivets. Temperature evolution at this region shows a rapid temperature increase immediately after the application of ultrasonic excitation at 1.2 sec.

![Fig. 13: Identified loose rivet and the related temperature evolution.](image)

CONCLUSIONS

Selected applications of thermographic nondestructive testing were presented. The measurements using vibrothermography and pulsed thermography were conducted for composite, steel and aluminum structures. The tests confirmed the effectiveness of thermographic testing methods for all analyzed cases.

Thermal Signal Reconstruction method was used for pulsed thermography. As expected, an improvement in the image quality was achieved while the amount of data to be stored for the analyzed thermographic sequence could be significantly reduced. Moreover, additional processing steps were successfully applied for automatic detection and determination of the area of damage.

The paper also presents two case studies for weld testing in steel samples and rivet testing in aircraft component. Vibrothermographic testing was performed on laboratory and mobile diagnostic systems. Obtained results confirmed the efficiency of vibrothermography in detecting closed defects.
REFERENCES